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Does correlated color temperature affect the ability of humans to identify veins?

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In the present study we provide empirical evidence and demonstrate statistically that white illumination settings can afxdfect the human ability to identify veins in the inner hand vasculature. A special light emitting diode lamp with high color rendering index (CRI 84–95) was developed and the effect of correlated color temperature was evaluated, in the range between 2600 K and 5700 K at an illuminance of 40±9 lx on the ability of adult humans to identify veins. It is shown that the ability to identify veins can, on average, be increased up to 24% when white illumination settings that do not resemble incandescent light are applied. The illuminance reported together with the effect of white illumination settings on direct visual perception of biosamples are relevant for clinical investigations during the night.

OCIS codes: *(330.0330) Vision, color, and visual optics; (330.5510) Psychophysics; (330.5020) Perception psychology; (170.2945) Illumination design; (230.3670) Light-emitting diodes.*

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1. Introduction

Lighting technology based on light emitting diodes (LEDs) is continuously developing by using new materials [1] and nanotechnology [2,3]. This fact results in an increase in the adaption of the technology to diverse environments such as automotive industry, general illumination etc. [4–6]. The environmentally friendly footprint of LEDs accompanied by the flexibility to design special spectral power distributions [7,8] and illumination levels make LED lighting systems the perfect candidate for hospital lighting [9–11]. Visual examination is the initial tool used by clinical doctors in all classes of medical diagnostics such as autotransplantation [12], subcutaneous and venous injections, venous cannulation [13–15], dental cleaning and diagnostics [16,17], and open surgery [18]. Several medical imaging techniques (photoacoustic imaging, fluorescent imaging, Raman imaging, multiphoton imaging and optical coherence tomography) and instruments (endoscopes and microscopes) have emerged recently offering "extended vision" to surgeons and medical doctors [19–23]. However, immediate visual clarity and thereby identification of specific entities is still an unresolved issue. Simulation programs for predicting the optimal spectral distribution of illuminants, for enhanced color difference between abnormal and normal tissue, have recently been reported successfully [24–26]. Moreover, exploration of color contrast through computation (NIST color quality simulation program software) according to CIE standards has shown that it is possible to enhance the contrast between color patches of typical tissue colors by using a special illuminant spectral distribution [24]. It has been shown in the past on artistic paintings that there can be a shift of preferred correlated color temperature (CCT) when comparing reality and simulation [27] and this effect is expected to be stronger for biosamples as the diversity and complexity of bio-tissue nuances is higher. Therefore, there is a need for visual inspection of real objects under real illumination (since simulation results may not represent reality).

In the present study the intention is to provide empirical evidence and investigate statistically if the CCT of the light source can affect the ability of humans to identify a specific type of biosample, namely the inner hand vasculature, and determine the optimal CCT according to human perception experience. Statistical confirmation of the success of the "optimal illuminant" versus traditional lighting systems by human eyes or even better during medical practice is of vital importance for the wide acceptance and implementation of the technology at hospitals. The spectral power distribution (SPD) of the light source used is such that the color rendering index (CRI) is high (84–95) in all light settings. Moreover, accessibility of veins is an everyday issue in hospital environments [28–30] that can be addressed by usage of expensive commercially available equipment [13,14,31].

Many studies have been carried out with the focus to discover the subjective preference for lighting conditions based on questionnaire-procedures or evaluate perception non-subjectively by visual acuity and contrast sensitivity tests [32–34], or [35–37]. Here the evaluation of the lighting is assessed by human eyes and is coupled with a "handling task" that involves time constraints and is not subjective. Non- subjective tests (d2-Alertness and concentration test [38]) have also been used for measuring and testing concentration under different lighting conditions; psychological and physiological processes in the human body can be affected by lighting conditions and might even induce positive effects on working speed and accuracy [39] or reduce anxiety [33].

2. Method

A. The lighting system

A multi-channel LED lamp was developed that allowed ramping the CCT of white light, with high CRI 84–95 (fig. 1), in the range 2600K to 5700K, while keeping the illuminance at the plane of interest (desk surface) within 40±9 lx. The various channels were permitting individual control of the intensities of colored (blue, cyan, green, red) and white LEDs (cold, neutral, warm). The spectra from the colored and white LEDs are shown in fig. 2. A LabVIEW program interface was constructed to control the light output [40]. The different white settings of the multi-channel LED lamp were created by adjusting the individual LED intensities and color mixing. The color mixing was achieved by using a reflector painted with Barium Sulfate ($BaSO_4$) and transmitting the light through a 3 mm thick plastic diffuser. Seven different white settings were investigated:

•Illumination 1: CCT 2600K, CRI: 94, 48lx;
•Illumination 2: CCT 3700K, CRI: 84, 31lx;
•Illumination 3: CCT 4400K, CRI: 89, 33lx;
•Illumination 4: CCT 4700K, CRI: 94, 36lx;
•Illumination 5: CCT 4900K, CRI: 95, 39lx;.
•Illumination 6: CCT 5400K, CRI: 94, 44lx; and
•Illumination 7: CCT 5700K, CRI: 94, 47lx.

The spectra of the 7 different white settings are shown in fig. 3. We are investigating the effect of illumination on the ability of a human subject to identify veins; more specifically we want to identify the optimal and poorest illumination CCT independently of human skin pigmentation.

Fig. 1. Black box illuminated with the multi-channel LED lamp at various correlated color temperatures. From left to right (upper line) 2600K, 3700K, 4400K, 4700K. From left to right (lower line) 4900K, 5400K, 5700K, 5700K. The last photo (lower line, right) shows the positioning of the handheld spectrometer on the plane of interest (desk surface). The color chart added allows the observation of color shifting due to the change of the illumination setting. The CRI is high in all settings (84–95).

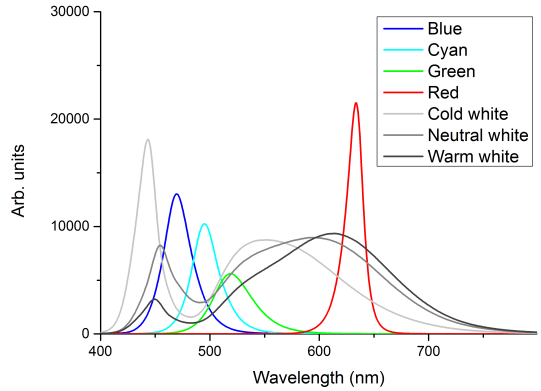

Fig. 2. Spectra from the colored and white LEDs used for the construction of the multi-channel LED lamp. Each channel was measured at 45% of its maximal performance.

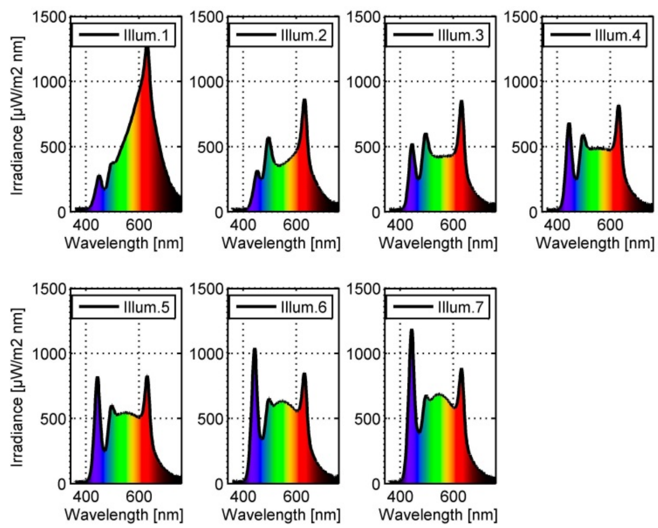

Fig. 3. Spectral power distributions of the 7 different white illumination settings. From left to right, upper line: The corresponding CCT and CRI are respectively 2600K, 94; 3700K, 84; 4400K, 89; 4700K, 94. From left to right, lower line: The corresponding CCT and CRI are respectively 4900K, 95; 5400K, 94; 5700K, 94.

For this reason, the yellow color (570-590 nm) is suppressed in all illumination settings, as a previous study has shown that among a population with diverse ethnicity the contrast between skin and vein varies most at these wavelengths [41]. Setting 1 resembles incandescent light and is intended to create a calm environment where the observer feels relaxed, a "warm", red enriched light. A similar effect is achieved with setting 2, but neither the SPD nor the CCT resemble incandescent light anymore. Settings 3, 4, and 5 are in the CCT region (4000-5000K) were RGB W_LEDs are reported to have optimal color enhancement ability for early detection of oral cancer [16]. In setting 6 and 7 the red components are suppressed in order to generate the impression of a cold-clean environment like the ones often observed in hospitals. As an illustration of the environment, the 7 different white light settings were reproduced by images in fig. 1. The color chart added in the illuminated box assists the illustration of the color shift as the light source changes from one setting to another.

The lamp was placed in a black painted box to minimize external distractions. The surrounding illumination was also eliminated to reduce interference from the external environment. The experimental setup is shown in fig. 4.

Fig. 4. Photograph of the experimental setup. The participant is sitting in front of a black box. The plane of interest is actually the hand surface which usually was positioned at the desk surface; where the drawing activity takes place.

The illuminance of each illumination setting was measured at the plane of interest. The observed illuminance variation among the different illumination settings is expected to have only a minor influence on the ability of humans to identify veins due to retinal gain-control mechanisms and visual adaptation [42]. The participants were allowed to move their hand freely in the box for achieving maximum performance. This action is expected to introduce variations in the real illuminance for a given illumination setting; the effect of these variations is likely to diminish any influence exerted on performance by the differences between the mean illuminances of the different illumination settings. It must be mentioned here that indoor lighting illuminances in hospitals are around 200–400lx., though these illuminance levels can disturb severely the circadian rhythm of the medical personnel working night shifts. The illuminance level applied here is around 40lx suitable for hospital function during night and evenings in order not to influence the circadian rhythm of the medical personnel [43].

B. Qualification and Quantification of ability to identify veins: Vein identification output (VIO)

The method to evaluate the human performance of identifying inner hand vasculature under various illuminations was established in terms of vein identification output. The vein identification output was defined to be the number of line-entities drawn by the participant to mimic the observed vasculature. In total thirty-four subjects participated in the experiment. A4-printing paper and blue pens were used for the drawings. The inner hand veins were selected for identification in order to focus the attention on color changes coming from the presence of veins and reduce effects due to protruded veins (light shadows, topography reflections). The vein identification output was not always an easy task to evaluate, so an estimation of the output over all illuminations was always done for each person after identifying that person's drawing style. By comparing a person's drawings among all the illumination settings (for one object), the best and worst performances were identified. Subsequently, intermediate performances were evaluated/scored from worst to the best. Finally, the number of line-entities and individual line segments was counted in the illumination setting that resulted in the medium performance, termed medium vein identification output (MVIO). When the MVIO was estimated, it was the within subject and object reference, for estimating the VIOs for the rest illumination settings. It is important to mention here that since the aim was to compare performance between different illumination settings (relative method), a reference was needed for rating the drawings, namely the MVIO within each subject and object; in this way a relative measure is introduced that is not dependent on intersubjective variations related to drawing style, ability to perform the task etc. The vein identification outputs in the rest of the illumination settings were calculated by identifying additional or lacking line-entities and individual line segments on the drawings with "extreme" performances, and by adding or subtracting respectively units to the MVIO. The VIO, as defined, should give an impression about how well or bad a vein pattern is visualized by a subject under a given illumination setting.

C. Procedure

A time interval of 1.5 minutes was given to the observer for each drawing, while a half minute rest was performed between the drawings. Moreover, a distraction period was inlayed in the process, namely drawing the periphery of the hand on the white paper before starting the time for drawing the veins. Instructions were given to the observers as following: 1) "Draw as many veins as you can see. You will have 1.5 minutes. I will give notice at the initialization and the end of each round." 2) "You have the freedom to move the hand around for optimal performance." 3) "Try not to recall where veins were." 4) "Draw only the veins you can see and try to replicate the shape/curvature of veins as well as possible." . Instruction 2, namely the freedom to move the hand around, brings the method closer to real life situations where for example nurses try to identify patients' veins for cannulation. The last instruction is giving to the task a short-term memory related character. Short-term memory cannot hold more than 5 to 9 elements per time [44]. The process of drawing/copying with the original design/object still in view does not involve any conscious effort to retain information in long term, and neither demands any organization of material held in memory. The subject identifies the vein; recalls its basic characteristics (length, shape, location on hand, location relative to other veins); draws the vein; and moves to the next. This trick (drawing/copying with object in view) in combination with instruction 3 is believed to minimize carry-over (learning effects) effects in the conscious level of the subjects as subsequent illumination settings are applied [45]. All in all, the procedure as instructed was intending to create no time intervals, where conscious effort could be done by the subjects to retain vein pattern information. In order to diminish any subconscious learning effects a randomized process for the order of the illumination settings was applied for each participant. In order to investigate if learning effects were significant and so affecting the final outcome of the analysis the average VIO was estimated, as a function of the kth order of drawing for 70% of the population. A typical drawing handed in by the participants after following the above mentioned instructions can be seen in fig. 5.

D. Experimental design and recruitment

Thirty-four observers participated in the experiment. There were 5 women and 29 men aged 18 to 68 years. All women were below 40 while 13 of the men were above 40. At the age of 40, the color of the lens of the human eye starts to become substantially more yellowish [46], so two age groups were defined. Age group 1 comprised 21 observers aged below 40; age group 2 comprised 13 observers equal or above 40. No separation among participants with abnormal visual acuity was performed in order to simulate a real life situation. Participants wearing glasses for correcting visual acuity were instructed to keep their glasses on during the experiment. However, color-anomalous observers were removed from the participants' sample. The screening was performed by using questionnaires. The population sample embraced many different nationalities, skin pigmentation varying from type I to type V according to the Fitzpatrick Scale [47]. The observers were all PhD students or employees at the Technical University of Denmark. The result is not expected to be biased from the scientific background of the participants. Moreover, the sequence of illumination settings was kept secret from all observers. The experiment consisted of two sub-experiments, one related to identification of veins on a reference hand (right hand) and one performed on the observer's hand (left hand). Left handed participants (1 subject) were not screened out from the subjects' sample; but were allowed to use their left hand for drawing while observing their right hand (subject shown in fig. 4). The sub-experiment on the reference hand was only performed with illumination settings 1, 2, 4 and 7. The sub-experiment on the reference hand is crucial for checking the hypothesis that regardless of the uniqueness of a person's eyes there was one universal CCT among the seven options that allowed optimal identification of veins for a vast majority of observers. It must be mentioned here that the same CCT could be achieved with various spectral power distributions [18], not all of them allowing such high color rendering index, and it would be interesting (in the future) to see what effect the specific spectral power distribution has on the vein identification ability. On the other hand, the sub-experiment on the observer's hand was of vital importance for testing the hypothesis that irrespective of variations in skin pigmentation, vein pattern etc. a CCT resulting in optimal performance for the identification of inner hand veins is found.

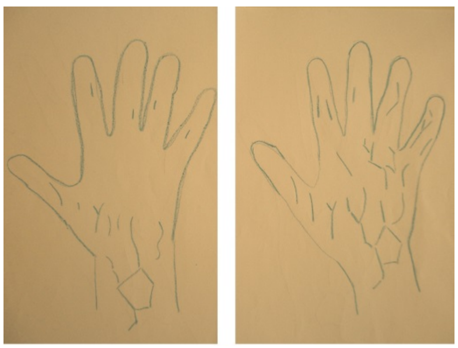

Fig. 5. A reproduction of two drawings from the same person from its own hand. Veins are marked as lines. The left side drawing is exhibiting an "MVIO situation", obtained under illumination setting 7. The right side drawing is exhibiting a "best performance situation" achieved under illumination setting 4. The vein identification outputs are respectively 21 (MVIO) and 38 (MVIO+17).

E. Statistical Analysis Method

To analyze the vein identification output, analysis of variance (ANOVA) was used (within subjects design) with a significance level of 0.05; using a mixed model with subject as a random effect and illumination as a fixed effect [48,49]. Additionally, gender and age were considered confounders [48] and adjusted for, by introducing them as fixed effects, as no special design of data acquisition was implemented in order to assure a "balance of design" for the experiment. An intercept is introduced to avoid comparison of illuminations to darkness. Furthermore, pairwise t-tests were used to detect differences among performances with the various illumination settings taken into consideration difference between individuals [50]. R was used as the statistical software for the analysis, and its machine precision is e-16 [51], in particular the functions lmer (lme4) [52,53], ANOVA, and t.test were used .

3. Results

A. Study 1: on reference object

The results of the within subject ANOVA showed a significant main effect of the illumination setting on the vein identification output, and the hypothesis of no effect due to illumination was strongly rejected p=4.8e-7<<0.05. On average, observers under light setting 1 (resembling incandescent light) performed worse on identifying veins than under illumination settings 2, 4 and 7 (table 1). Only for 5.9% of the population that statement didn't hold. The best average performance was achieved under illumination setting 4 (CCT 4700K). Moreover, 41 % of the participants attained their best performance under setting 4 the residual 59 % of the population was distributed among the rest of the illumination settings, as shown in Fig 6.

Table 1. Average vein identification outputs and standard deviations for the reference object under the various illumination settings applied.

Illumination setting	Average vein identification output	Standard deviation of vein identification output	Average performance improvement %[a]
1(CCT:2600K)	19.3	0.9	Not applicable
2(CCT 3700K)	22.5	2.3	16.6
4(CCT:4700K)	24.0	2.3	24.3
7(CCT:5700K)	23.1	2.3	19.7

[a]The average performance improvement % is calculated in relation to illumination 1 (resembling incandescent light).

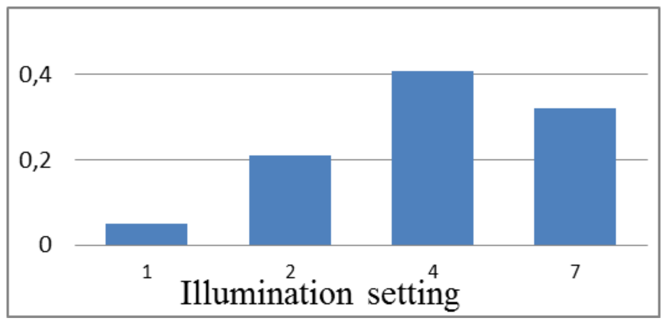

Fig. 6. Distribution of population achieving maximum performance under the various illumination settings.

The pairwise t-tests didn't show significant differences among performances under illumination settings 2, 4 and 7 (table 2). To the contrary, performances under illumination setting 1 (resembling incandescent light) were significantly different from those under illumination settings 2, 4 and 7.

Table 2. P-values from the pairwise t-tests among various illumination settings applied. Illuminations 2, 4 and 7 do not appear to be significantly different from each other.

P-values	Illum. setting 1	Illum. setting 2	Illum. setting 4	Illum. setting 7
Ill. setting 1	1	3e-5	3e-6	5e-5
Ill. setting 2	3e-5	1	0.13	0.43
Ill. setting 4	3e-6	0.13	1	0.29
Ill. setting 7	5e-5	0.43	0.29	1

1. *Effect of age and gender*

Statistically significant effects were found for the impact of illumination on the vein identification output. In order to verify if age and gender could play a role as confounders, supplementary analysis was performed. Results indicated that on average older observers performed worse on the task; the vein identification output reduced on average by 2.4. However, significance levels were not reached (p-value 0.16) for rejecting the hypothesis of no effect of age. Similarly, male observers performed on average worse than female; the vein identification output decreased on average by 1.9. However, significance levels were not reached (p-value 0.42) for rejecting the hypothesis of no effect of gender. It must be mentioned that all women in the study were young (below 40) so their increased average performance was expected from the observed age-related tendency.

The interaction plot between age and illumination settings can be seen in fig. 7.

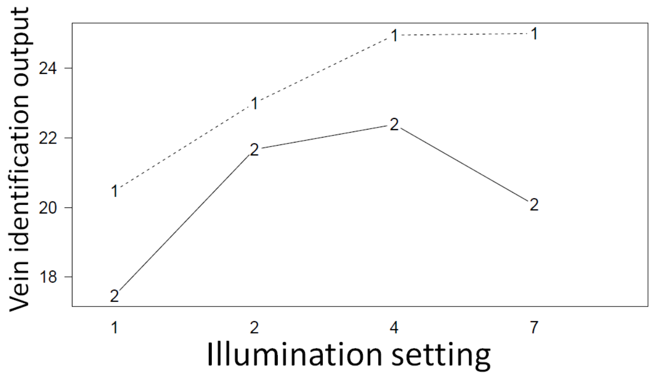

Fig. 7. Vein identification output as a function of illumination setting for a reference object. Interaction plot for age and illumination settings (line 1/dotted shows the average output of younger observers, line 2/continuous shows the average output of subjects over the age of 40).

It is interesting to observe that for older observers (only males), there was a bigger impact of the illumination setting on performance than that observed for younger observers (males and females) though no significance was reached (the population of old males was small).

2. *Learning Effect*

In order to test if any learning effect was present at the process with the reference object, creating bias to the final outcome; we investigated if the average VIO is increased as a function of the order in which the illumination setting was applied (Fig. 8). Similarly, the average VIOs across all drawings produced by all participants in the kth drawing were calculated (1st drawing 21.14, 2nd drawing 21.75, 3rd drawing 22.3, 4th drawing 22.3). None of the analysis indicated that significant learning effect took place for the reference object.

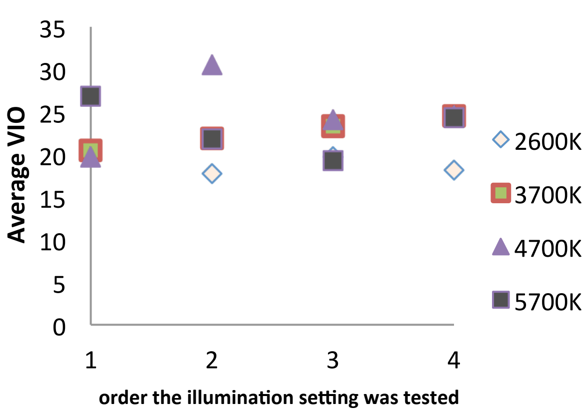

Fig. 8. Vein identification output as a function of the order in which the illumination settings were used for the reference object. No significant upward trend is observed as the order is increased, supporting insignificant learning effects.

B. Study 2: on test object

The results of the within subject ANOVA showed a significant main effect of the illumination setting on the performance of observers on a test object, and the hypothesis of no effect due to illumination setting was rejected p=0.029<<0.05. The average vein identification output of observers under the various illumination settings is shown in Table 3.

Table 3. Average vein identification outputs and standard deviations for random object, when the seven different illumination settings are applied.

Illumination setting	Average vein identification output	Standard deviation of vein identification output	Average performance improvement %[a]
1 (2600K)	17.1	2.6	Not applicable
2 (3700K)	19.2	3.5	12.3
3 (4400K)	18.2	3.5	6.4
4 (4700K)	20.2	3.5	18.1
5 (4900K)	19.1	3.5	11.7
6 (5400K)	18.6	3.5	8.8
7 (5700K)	18.6	3.5	8.8

[a]The average performance improvement % is calculated in relation to illumination 1 (resembling incandescent light).

The highest average performance was achieved when the light source was running under setting 4 (CCT 4700K). Furthermore, 35 % of the studied population managed to reach the highest VIOs on their own hands under this setting. The distribution of maximum performances in all light settings is presented in Fig. 9. It must be mentioned here that for 23.4% of the population the maximum performance (maxVIO) was observed in more than one illumination setting. Pairwise t-tests showed significant differences in performance only between illumination setting 1 (resembling incandescent light) and each of the other settings (p.value 0.01). Lower illuminances are not expected to improve visualization; the fact that illumination setting 1 (providing the highest illuminance) resulted in the worst performance supports the hypothesis that visualization of veins can be improved by applying illumination settings with a CCT higher than 2700K at the same illuminance (illumination setting 7) and even at lower illuminance (illumination settings 2, 3, 4, 5, 6). A CCT of around 2700K is a typical value for incandescent lamps.

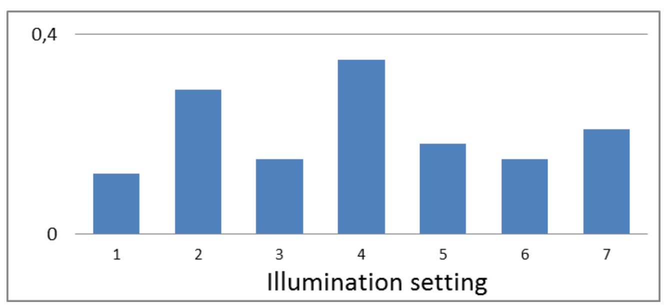

Fig. 9. Distribution of population achieving maximum performance under the various illumination settings.

1. *Effect of age and gender*

Results indicated that on average older observers performed worse on the task; the vein identification output was reduced on average by 3.6. However, significance levels were not reached (p-value 0.09) for rejecting the hypothesis of no effect of age. Similarly, male observers performed on average worse than female; vein identification output decreased on average 0.1. However, significance levels were not reached (p-value 0.98) for rejecting the hypothesis of no effect of gender. It must be mentioned that since the statistical design was not designed to be balanced (only young females participated in the study) the interpretation of the results regarding age and gender need to be interpreted cautiously. The interaction plot between age and illumination settings can be seen in fig. 10.

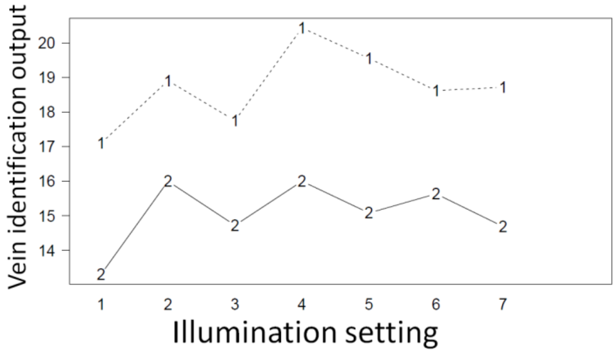

Fig. 10. Vein identification output as a function of illumination setting for the test objects. Interaction plot for age and illumination settings (line 1/dotted shows the average output of younger observers, line 2/continuous shows the average output of older observers).

2. Learning Effect

In order to test if any learning effect was present at the process with the test object, creating bias to the final outcome, we investigated if the average VIO is increased as a function of the order in which the illumination setting was tested (fig. 11). Similarly, the average VIOs across all drawings produced by all participants in the kth drawing were calculated (1st drawing 17.33, 2nd drawing 17.13, 3rd drawing 17.5, 4th drawing 17.58, 5th drawing 17.08, 6th drawing 16.27, 7th drawing 18.64). None of the analysis indicated that significant learning effect took place for the test object.

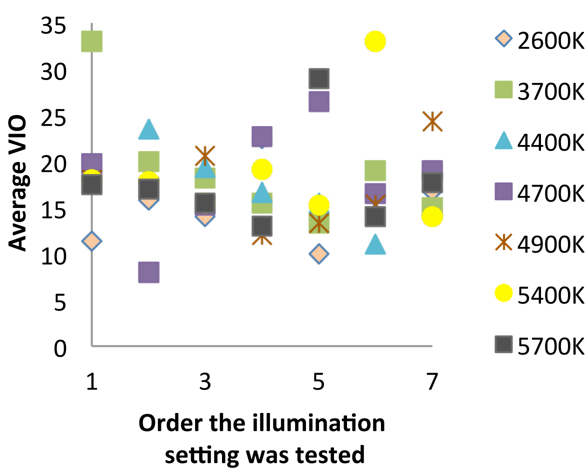

Fig. 11. Vein identification output as a function of the order in which the illumination settings were applied for the test object. No significant upward trend is observed as the order in increased, supporting insignificant learning effects.

4. Discussion and Conclusion

It is clear that the ability of visual identification and enhanced color contrast is critical for improving efficiency and performance in medical practice. Imaging techniques offering high contrast and resolution have emerged over the recent years supporting both better diagnosis and treatment of patients. However, often these imaging techniques are expensive, the maintenance of the equipment can be demanding and only trained and experienced medical personnel can operate it. On the other hand, immediate visual examination is the first tool used by medical practitioners (nurses, doctors and surgeons) in all situations, but how to enhance immediate visual clarity and color contrast is still an unanswered issue. In this work a first step is done towards assessing a statistical "human eye evaluation" of seven different illumination settings, for easier vein identification; while eliminating the influence of personal preference.

It was shown that the human ability to identify hand veins can be enhanced or weakened depending on the white light setting (ramping CCT value). More specifically, when participants were under illumination settings 2, 3, 4, 5, 6 and 7 they performed in average better than under illumination setting 1. Illumination setting 1 resembled light produced by incandescent lamps (CCT at 2600K). The difference among VIOs produced under illuminant settings with a CCT within the interval 3700–5700K, were proven not to be significantly different. Under illumination setting 4 the performance was increased in average by 18% on a test object (and 24% on a reference object) compared to setting 1. The SPD of all light settings was designed in order to achieve CRI values above 84 that would assure satisfactory color reproduction in a hospital environment. Moreover, the illuminance was designed in order to disturb as little as possible the circadian rhythm of medical personnel during night shifts. The suggested light settings produced by an LED lamp have the advantage of the combination of a good color rendering of objects, the enhanced direct visibility and low energy consumption in comparison with other competing technologies such as energy saving bulbs, red light sources or incandescent lamps.

Application driven optimization of general illumination can be critical in hospital environments. In this study optimization of the CCT of the light source towards enhanced color contrast of the inner hand vein pattern was tested. Apart from the CCT also the SPD and illuminance could contribute in future optimization. Moreover, human eyes would respond differently to different types of biosamples as different nuances of colors come into play, so further research is essential for optimizing SPD, CCT and illuminance for different types of biosamples.

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